

PROBING SHORT RANGE NUCLEON CORRELATIONS IN HIGH ENERGY HARD QUASIELASTIC pd REACTIONS

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Abstract

We show that the strong dependence of the amplitude for NN hard scattering on the collision energy can be used to magnify the effects of short range nucleon correlations in quasielastic pd scattering. Under specific kinematical conditions the effect of initial and final state interactions can be accounted for by rescaling the cross section calculated within the plane wave impulse approximation. The feasibility to investigate the role of relativistic effects in the deuteron wave function is demonstrated by comparing the predictions of different formalisms. Binding effects due to short range correlations in deuteron are discussed as well.

1 Introduction

The deuteron is the simplest and best understood nuclear system bound by strong interactions. As such it has received an extraordinary amount of attention. The binding energy of the deuteron is rather small compared to the nuclear potential and to the binding energy of heavier nuclei and the average distance between the nucleons in the deuteron is larger than the typical distance in nuclei. At first glance these facts would seem to discourage one from using the deuteron for studying short range correlations (SRC) between nucleons. However, a conventional theory of the deuteron based on a phenomenological potential of the nucleon-nucleon interaction with a repulsive core at small distances predicts a fairly substantial contribution of high-momentum nucleon components in the wave function (WF) [1]. Note that the Fourier transform of the deuteron WF implies that high momentum nucleon components originate predominantly from SRC.

The recent measurements of elastic magnetic, electric and quadrupole form factors at $Q^2 \leq 1 \text{ GeV}^2$ [2] as well as previous data for elastic [3, 4] and nearthreshold ed [5] scattering at Q^2 up to 10 GeV^2 , elastic pd scattering [6] and the backward production of secondary p, π on the deuteron [7, 8] are all consistent with a conventional nonrelativistic theory of the deuteron which has a core in the NN force (see e.g. [9]). All these data show that the probability to find a nucleon with momentum above $0.3 \text{ GeV}/c$ in the deuteron wave function is at the level of $3 - 5\%$ and furthermore, that the D wave dominates for the high momentum components.

Although the above experiments establish the presence of SRC in the deuteron any detailed knowledge of the high momentum components in the deuteron WF is quite limited. The elastic and inclusive (e, e') cross sections depend on an integral over nucleon momenta in the deuteron. Also, the inclusive character of the backward particle production does not allow the unambiguous reconstruction of the space-time picture of these processes.

High energy wide angle exclusive reactions belong to the special class of processes which can probe rather directly the structure of SRC in the deuteron. The ability to

measure simultaneously the spectator and the interacting nucleons opens up a unique opportunity to cross check various interpretations of SRC dominated phenomena. This is the reason why we consider the high energy exclusive reactions to be the most straightforward method for investigating SRC. It is a timely venture to investigate theoretically these processes on the deuteron since the high accuracy facilities for studying these processes experimentally with high intensity proton [12] and electron [13] beams will be available very soon.

In this paper we analyze the capacity for studying SRC in the deuteron by a complete kinematical measurement of the hard proton-deuteron quasielastic scattering. The salient feature of this reaction (discussed in section 2) is that within the framework of the plane wave impulse approximation (PWIA) the strong energy dependence of the hard pp elastic cross section boosts the contribution of the high momentum components of the wave function[14]. We show (section 3) that initial and final state interactions do not spoil this conclusion. In section 4 we show that there is a significant difference between two varying approaches to the description of deuteron structure which enables us to demonstrate the importance of relativistic effects. The fact that the processes are sensitive to high momentum components of the deuteron WF can be also used to investigate models of the EMC effect. In order to demonstrate that, we calculate the effect of the suppression of point-like configurations due to SRC [15]. In the Appendix we present some details of the calculation of the initial and final state interactions.

2 Plane Wave Impulse Approximation

When calculating the cross sections of hard processes it is necessary to include relativistic kinematics and the fact that high energy processes are developed along the light cone (LC). We calculate the cross section for the quasielastic $d(p, 2p)n$ reaction within the light-cone impulse approximation. In Section 4 we show that for small spectator momenta in the deuteron the predictions based on LC mechanics are indistinguishable from those

based on a nonrelativistic theory. Within the LC impulse approximation the cross section is a convolution of the elementary pp cross section and the deuteron light cone density function [9]:

$$\frac{d^6\sigma}{(d^3p_3/E_3)(d^3p_4/E_4)} = \kappa_p \frac{1}{2\pi} \frac{\tilde{s}^2 - 4m^2\tilde{s}}{2m \cdot |\vec{p}_1|} \cdot \frac{d\sigma^{pp}}{dt}(\tilde{s}, t) \cdot \frac{\rho_D(\alpha, p_t^2)}{\alpha^2 p_{D-}} \delta(p_{s+} - \frac{m^2 + p_t^2}{m(2 - \alpha)}) \quad (1)$$

where

$$\alpha = \alpha_4 + \alpha_3 - \alpha_1 ; \alpha_i = 2 \frac{p_{i-}}{p_{D-}} \equiv 2 \frac{E_i - p_i^z}{E_D - p_D^z} ; p_t = p_3^t + p_4^t$$

$$\tilde{s} = (p_3 + p_4)^2 \approx 2m^2 + 2E_1 m \alpha - \frac{\alpha}{2} \left(4 \frac{m^2 + p_t^2}{\alpha(2 - \alpha)} - m_D^2 \right) ; t = (p_1 - p_3)^2 \quad (2)$$

where $p_D = (E_D, \vec{p}_D)$, $p_1 = (E_1, \vec{p}_1)$, $p_3 = (E_3, \vec{p}_3)$, $p_4 = (E_4, \vec{p}_4)$, $p_s = (E_s, \vec{p}_s)$ are the four - momenta of the target nucleus, incoming, scattered, produced and spectator nucleons, respectively (see e.g. Fig.4c). The indices "t" and "z" denote the transverse and longitudinal direction with respect to the incoming proton momentum \vec{p}_1 . The "+" and "-" denote the energy and longitudinal components of the four-momenta in the light cone reference frame: $p_{\pm} = E \pm p_z$. The factor κ_p accounts for the effects of initial and final state interactions. In the plane wave approximation $\kappa_p = 1$.

The light-cone density function of deuteron expressed in terms of S and D components of the wave function is as follows [11]:

$$\rho_D(\alpha, p_t^2) = \frac{u(k)^2 + w(k)^2}{2 - \alpha} \cdot \sqrt{m^2 + k^2};$$

$$k \equiv k(\alpha, p_t) = \sqrt{\frac{m^2 + p_t^2}{\alpha(2 - \alpha)} - m^2} ; (0 < \alpha < 2) \quad (3)$$

Note that in eq. (3) we ignore possible admixtures of non-nucleonic degrees of freedom in the WF. This is justified by the analysis of high energy processes on the deuteron which indicate that the nucleon-nucleon component of deuteron WF dominates in the region of momenta below $(0.5 \sim 0.6) \text{ GeV}/c$ (for a review see [10]).

We write $\frac{d\sigma^{pp}}{dt}$ for the invariant cross section for elastic pp scattering. We use phenomenological pp differential cross section parameterized by:

$$\frac{d\sigma^{pp}}{dt}(s, t) = 45.0 \frac{\mu b}{sr GeV^2} \cdot \left(\frac{10}{s}\right)^{10} \cdot \left(\frac{2 \cdot t}{4m^2 - s}\right)^{-4\gamma} \cdot \left[1 + \rho_1 \sqrt{\frac{s}{GeV^2}} \cdot \cos \phi(s) + \frac{\rho_1^2}{4} \frac{s}{GeV^2}\right] \cdot F(s, \theta_{c.m.}) \quad (4)$$

where $\rho_1 = 0.08$, $\gamma = 1.6$ and $\phi(s) = \frac{\pi}{0.06} \ln(\ln[s/(0.01 GeV^2)])^{-2}$. At $s > \sim 6.5 GeV^2$ eq.(4) reproduces the parameterization of Ralston and Pire [16] for $\theta_{c.m.} = 90^\circ$ while at fixed s it reproduces the parameterization of Brodsky [17]. The function $F(s, \theta_{c.m.})$ is used to further adjust the phenomenologically motivated parameterization of the experimental data in the range $60^\circ \leq \theta_{c.m.} \leq 90^\circ$. We present the function $F(s, \theta_{c.m.})$ for four typical $c.m.$ scattering angles (Fig.1). At the limit of large s and large $c.m.$ scattering angle the phenomenological motivated approximation is the best and $F(s, \theta_{c.m.})$ approach unity. As far as we get from the ideal case the larger $F(s, \theta_{c.m.})$ is. For cross sections at lower s we use the phase-shifts generated by the SAID code [18].

We draw attention to the strong dependence on s of the elementary cross section. According to eq. (4), for a fixed value of $-t$ ($\geq 2 GeV^2$), the pp cross section behaves as $\sim s^{-(10-4\gamma)}$ which according to eq. (2) will introduce a $\sim \alpha^{-(10-4\gamma)}$ dependence in the PWIA cross section (see eq. (1)). Thus, in PWIA the cross section for proton wide angle scattering on the deuteron is sensitive to the low α values of the wave function [14] i.e. to that high Fermi momentum of the struck nucleon which is predominantly parallel to the incoming beam. This is the key feature that makes the process a useful tool to magnify SRC effects. Indeed it complements other probes such as electrons which are usually more sensitive to the $\alpha \geq 1$ region.

We calculated the cross sections using eqs.(1)-(4). They are shown in Fig.2 as a function of the momentum (p_s) and polar angle (θ_s) of the spectator neutron with respect to the incoming proton. One can see a significant enhancement of the cross section for

large momenta of the spectator nucleon at large projectile momenta ($\geq 12 \text{ GeV}/c$) and when the target proton momentum ($\theta_2 = \pi - \theta_s$) tends to be parallel to the projectile. Thus the discussed process is rather sensitive to the high momentum part of the deuteron wave function which in turn is the result of the strong s dependence of the elementary pp cross section. Because of this strong s dependence it is necessary to pay special attention to off-shell effects, which are proportional to the difference between the invariant energies at the intermediate (s_{in}) and final (\tilde{s}) states. Since in LC mechanics only the "–" and "t" components of momenta are conserved in an intermediate state, this difference is:

$$s_{in} - \tilde{s} = m_D \cdot (2E_s - m_D) + p_{1-}(p_2 - (p_D - p_s))_+ = m_D \cdot (2E_s - m_D) + \frac{p_{1-}}{m\alpha} \cdot m_D(2E_s - m_D) \quad (5)$$

where $p_{2+} = \frac{m^2 + p_{st}^2}{m\alpha}$. The difference between s_{in} and \tilde{s} does not increase with incoming energy since $p_{1-} = E_1 - p_1 \rightarrow 0$. We estimate the size of the effect by calculating the cross section with eq.(1) for two values of the invariant energy \tilde{s} and s_{in} . The two calculations were done for the kinematics where the projectile is parallel to the struck proton and the results are shown in Fig.3. Note that the off-shell effects depend only weakly on the direction of the struck nucleon momentum (see eq.(5)). We see also that the off-shell effects cause at most $\approx 10\%$ change in the cross section values for spectator momenta up to $\sim 0.3 \text{ GeV}/c$.

Since the kinematics of quasielastic scattering on a deuteron is fully determined by the momenta of the two ejected protons one can reconstruct the geometry of the elementary pp hard scattering. We calculate the cross sections for three extreme geometries where the momentum of the struck nucleon is parallel, antiparallel and perpendicular to the direction of the incident proton and we refer to them accordingly as parallel, antiparallel and perpendicular.

3 The Effects of Initial and Final State Interactions

In order to extract usefull information from the data one has to account for the initial state interaction (ISI) of the incoming proton and the final state interactions (FSI) between the outgoing protons and the spectator neutron.

We will choose kinematical conditions such that the ISI and the FSI corrections will be small or, at least, will not introduce any additional energy dependence in the spectra of scattered nucleons.

We will use the eikonal approximation to calculate the sum of the diagrams shown in Fig.4 which describe the hard PWIA scattering (Fig.4a) and the lowest order soft NN rescatterings (Fig.4b-d). The soft interactions between the incident and target protons as well as the interactions between the scattered and produced protons are included in the phenomenological parameterization of the pp hard scattering amplitude.

Since at high energies the soft rescattering amplitude depends almost linearly on the energy of the collision s , the contribution of the ISI diagram (Fig.4b) is equal to the contribution of any one of the FSI (Fig.4c,d) diagrams. Therefore, just one of the three diagrams (b,c,d) has to be evaluated and the final result is given by the PWIA diagram plus three times the contribution from any one of the rescattering diagrams (see details in the Appendix). Since the soft scattering decreases exponentially with transfered momentum while the hard scattering has a power law dependence it is convenient to factorize the effect of ISI and FSI into a scale factor κ_p :

$$\begin{aligned} \kappa_p = & 1 - \frac{3}{2} \int \frac{u(k)u(k') + w(k)w(k')[\frac{3}{2}\frac{(kk')^2}{k^2k'^2} - \frac{1}{2}]}{u^2(k) + w^2(k)} \left(\frac{\sqrt{m^2 + k'^2}}{\sqrt{m^2 + k^2}} \right)^{\frac{1}{2}} \cdot f(q_t) \cdot \frac{d^2 q_t}{(2\pi)^2} + \\ & \frac{9}{16} \int \frac{\left(u(k_1)u(k_2) + w(k_1)w(k_2)[\frac{3}{2}\frac{(k_1 k_2)^2}{k_1^2 k_2^2} - \frac{1}{2}] \right) \left(\sqrt{(m^2 + k_1^2)(m^2 + k_2^2)} \right)^{\frac{1}{2}}}{(u^2(k) + w^2(k)) \sqrt{m^2 + k^2}} \cdot f(q_{1t})f(q_{2t}) \frac{d^2 q_{1t}}{(2\pi)^2} \frac{d^2 q_{2t}}{(2\pi)^2} \end{aligned} \quad (6)$$

where $k = k(\alpha, \vec{p}_t)$, $k' = k'(\alpha, \vec{p}_t + \vec{q}_t)$, $k_1 = k_1(\alpha, \vec{p}_t + \vec{q}_{1t})$, $k_2 = k_2(\alpha, \vec{p}_t + \vec{q}_{2t})$ are given

by eq. (3) and $f(q_t)$ is the imaginary part of the elastic NN soft scattering amplitude. For simplification we assumed that $f(q_t) = \sigma_{tot}^{NN} \exp(-bq_t^2)$ and neglected nucleon spin rotations in the LC which may add uncertainties of the order of 1% (see [19] for estimates).

The Eq.(6) contains the distinctive feature of soft high energy processes that the α component of the target nucleon momentum is conserved in soft rescatterings. In Fig.5 we present the value of κ_p as a function of α for different values of the spectator transverse momenta (p_s^t). It shows that the ISI and FSI are significant for $|\alpha-1| \geq \sim 0.3$ for any p_s^t and at large p_s^t ($> \sim 0.1 \text{ GeV}/c$), for a large range of α . In these kinematical conditions the contribution from higher order rescatterings is not negligible and consequently our results could not be trustworthy. The important feature of ISI and FSI is that at small p_s^t the κ_p is a smooth function of α for $0.7 \leq \alpha \leq 1.3$, which corresponds to spectator momenta $|\vec{p}_s| \leq 0.25 \text{ GeV}/c$ in parallel geometry and $|\vec{p}_s| \leq 0.4 \text{ GeV}/c$ in antiparallel geometry. In these cases the difference of κ from 1 is typically $\leq 20 \sim 25\%$ and the effects of initial and final state interactions can be accounted for by rescaling the PWIA cross section. Thus, quasielastic processes with small p_s^t and α within the above discussed kinematical range are well suited for investigating high momentum nucleon component in the deuteron. It means that under these conditions the deuteron is a good testing ground for the studying the basic ingredients of the nucleon - nucleon interaction.

Note that in this paper we do not consider any possible effects due to color transparency (see e.g. [27] and references therein) which could suppress considerably the effects of ISI and FSI especially at larger projectile energies. We will elaborate on the physics of color transparency in forthcoming publications.

4 Comparision Between Different Approaches

An interesting question is to what extent the effects due to the nucleon relativistic motion in the deuteron are important and whether they can be investigated experimentally.

In Fig.6 we show two time-ordered diagrams which represent the standard impulse approximation contribution (A) with on - energy shell NN amplitude and the relativistic contribution (B). To examine to what extent the relativistic contribution (diagram B) is important we compare the results obtained in the light-cone impulse approximation with those of the virtual nucleon formalism (VN) (see e.g. [20]):

$$\frac{d^6\sigma}{(d^3p_3/E_3)(d^3p_4/E_4)} = \kappa_p \frac{1}{2\pi} \frac{\tilde{s}^2 - 4m^2\tilde{s}}{2m \cdot |\vec{p}_1|} \frac{d\sigma^{pp}}{dt} \cdot \frac{u^2(p_s) + w^2(p_s)}{N(E)} \delta(E_s - (M_D - E)) \quad (7)$$

where $E = E_3 + E_4 - E_1$. The factor $N(E) = 2E/M_D$ accounts for the conservation of baryon charge [21].

In the LC impulse approximation we know (see e.g. [22], [9]) that the contribution of diagram B is negligible or included into the definition of the deuteron wave function. By comparing the LC impulse approximation to the VN approximation, where diagram B is included in different way, we actually can learn about the importance of diagram B.

It is interesting to note that we account for ISI and FSI in the virtual nucleon impulse approximation by an equation which is very similar to eq.(6). The only major difference with the LC approximation is the different argument (momentum) of the deuteron wave function.

The ratio of the cross sections calculated in the LC impulse approximation (eq. (1)) and in the virtual nucleon approach (eq. (7)) is shown in Fig.7. The ratio is displayed as a function of the spectator (neutron) momentum for the above defined parallel (antiparallel) and perpendicular geometries. We use deuteron wave functions calculated with the Bonn[23] and Paris [24] potentials. Formally, the main difference between the LC and virtual nucleon formalisms is in the value of the momentum at which the deuteron wave function is calculated by eq. (3). For the perpendicular geometry as well as for small spectator momenta $\leq 0.1 \text{ GeV}/c$ the 'internal' momentum k and the spectator momentum in the laboratory system are rather close to each other. Under those conditions there is no substantial difference between the relativistic and non-relativistic calculations. However, there is a considerable ($\sim 20 - 25\%$) difference between these approaches even

at relatively low spectator momenta of about $\sim 0.25 \text{ GeV}/c$ where the deuteron wave function is known with an accuracy of a few percent and where the ISI and FSI can be replaced by a rescaling factor (see previous section).

Another way to confront various approaches that account for the relativistic motion of nucleons in the deuteron is to measure the asymmetry between the cross sections for parallel and antiparallel geometries at light-cone momentum fractions α and $2 - \alpha$. We define the asymmetry parameter $A(\delta)$ as [25]:

$$A(\delta) = \frac{f(1 - \delta) - f(1 + \delta)}{[f(1 + \delta) + f(1 - \delta)]/2} \quad (8)$$

where $f = \frac{\alpha^2 \sigma^{pD}}{(s^2 - 4m^2 s) \cdot \sigma^{pp}}$ (see eq. (1)) and $\alpha = 1 - \delta$, $2 - \alpha = 1 + \delta$.

Since the light-cone formulae (eq. (1) and eq. (6)) are invariant under exchange of α and $2 - \alpha$ we get that $A(\delta) = 0$. This is because the two nucleons in the deuteron are treated symmetrically in light-cone quantum mechanics. In contrast, in the virtual nucleon description the interacting nucleon is off-shell while the spectator is on the mass shell. As a result the symmetry with respect to the $\alpha \Leftrightarrow 2 - \alpha$ transposition is lost. The significance of this effect can be seen in Fig.8 which shows the asymmetry calculated in the VN approximation according to eq. (8). A significant difference between the LC prediction ($A(\delta) = 0$) and the VN one $A(\delta) \approx 0.5$ reveals itself at comparatively low spectator momenta $p_{sz} \sim -0.25 \text{ GeV}/c$ for parallel and $p_{sz} \sim 0.34 \text{ GeV}/c$ for antiparallel geometries. The initial and final state interactions plays insignificant role at low spectator momenta (cf. above discussion) and will even enhance the difference at higher momenta.

One can also investigate the difference between the two approaches by looking at the symmetry of the cross sections under the transformation which changes the sign of the spectator momenta \vec{p}_s . Such a symmetry is expected in the VN approximation eq.(7) but not in the light-cone description eq.(1).

It is worth mentioning that at the large energies of the experiment where one measures the two emerging protons will yield a better resolution in α than in p_s [26]. Therefore, from a practical point of view there is an advantage in testing the asymmetry in α rather

than in p_s . The ISI and FSI effects suppress the sensitivity to the various deuteron wave functions as can be seen in Figs. 7 and 8. The suppression occurs because the integrals in eq. (6) are sensitive mainly to the lower momenta in the deuteron wave function.

The fact that the target nucleon is bound in a deuteron can significantly alter the picture of high-energy hard scattering especially for the large momenta. One consequence of nucleon binding is the suppression of point - like configurations for bound nucleons [15]. At distances where the two-nucleon interaction is dominated by the attractive part of the nucleon-nucleon potential the probability of small size quark-gluon configurations (point-like configurations (PLC)) is suppressed (color screening phenomenon [27]). For the discussion how this effect reveals itself in the interaction of two nucleons see [28]. The amount of suppression can be estimated by multiplying the deuteron LC wave function by the factor [15]:

$$\delta(k, t) = \left(1 + \Theta(t_0 - t) \cdot \left(1 - \frac{t_0}{t} \right) \cdot \frac{\frac{k^2}{m_p} + 2\epsilon_D}{\Delta E} \right)^{-2} \quad (9)$$

where ϵ_D is the deuteron binding energy and ΔE ($\approx 0.6 \text{ GeV}$) is a parameter which characterizes the bound nucleon excitation in the deuteron. The additional t dependence $(1 - \frac{t_0}{t})$ [29] accounts for the fact that point - like configurations dominate in the bound nucleon wave function for reactions with sufficiently large transferred momentum t . We used the value $t_0 = -2 \text{ GeV}^2$. In Fig.9 we show the suppression of PLC as a function of the spectator momentum for the parallel, perpendicular and antiparallel geometries. Except for very large spectator momenta the effect is the same for the various geometries. The suppression is relatively small in the parallel geometry for $p_s \geq 0.5 \text{ GeV}/c$ due to the small energy transfer in this kinematical condition. This is a consequence of the t dependence in eq. (8). The PLC suppression decreases the cross section and increases the difference between the LC and VN approximations for parallel kinematics (solid line in Fig.9). Note also that for $|t| \gg 2 \text{ GeV}^2$ the t dependence becomes weaker and that the symmetry under $\alpha \Leftrightarrow 2 - \alpha$ transformation is restored.

5 Conclusion

We summarize our results in Fig.10 where we display the cross section for hard quasi-elastic proton scattering on the deuteron by taking into account the various SRC effects discussed in this paper. We see that ISI and FSI and nuclear binding effects do not mask the predicted enhancement of high momentum components for parallel kinematics.

We reiterate that a fully kinematical measurement at the appropriate kinematical conditions makes it possible to separate the various effects we discussed. For example, at neutron spectator momenta of about $250 \text{ MeV}/C$, where the deuteron wave functions are well known, any difference between a bound and a free nucleon in parallel kinematics tends to increase the differences between the light-cone and virtual nucleon results. Also the contributions from ISI and FSI are small and have a relatively weak momentum dependence.

We have shown that there is considerable difference for the asymmetry of cross sections in parallel and antiparallel geometries when calculated in the LC and VN approximations in a kinematical region where ISI and FSI effects and effects of EMC are well understood. These differences allow us to determine the importance of the vacuum diagram contribution. Eventually, after we achieve some understanding of hard scattering, nucleon binding, ISI and FSI effects, any new data will be able to teach us something about the deuteron WF at momenta above the region studied thus far.

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Appendix

To account for the initial state interaction of the incoming proton and of the final state interaction of the scattered and knocked out protons with the spectator neutron we need to calculate the sum of the diagrams in Fig.4:

$$\begin{aligned}
T_D^{if} = & T^h(q) \cdot \psi(\alpha, p_t) \\
& - \int_{(b)} \frac{T^h(s, t') \cdot T^s(k)}{((p_s - k)^2 - m^2 + i\varepsilon)((p_1 - k)^2 - m^2 + i\varepsilon)} \cdot \psi(\alpha + \alpha_k, p_t + k_t) \cdot \frac{d^4 k}{i(2\pi)^4} \\
& - \int_{(c)} \frac{T^h(s', t') \cdot T^s(k)}{((p_s - k)^2 - m^2 + i\varepsilon)((p_3 + k)^2 - m^2 + i\varepsilon)} \cdot \psi(\alpha + \alpha_k, p_t + k_t) \cdot \frac{d^4 k}{i(2\pi)^4} \\
& - \int_{(d)} \frac{T^h(s', t) \cdot T^s(k)}{((p_s - k)^2 - m^2 + i\varepsilon)((p_4 + k)^2 - m^2 + i\varepsilon)} \cdot \psi(\alpha + \alpha_k, p_t + k_t) \cdot \frac{d^4 k}{i(2\pi)^4}
\end{aligned} \tag{10}$$

where $s' = s - 2(p_3 + p_4)_t k_t - k_t^2$, $t' = t - 2p_3 k_t - k_t^2$ and $\alpha_k = \frac{k_-}{m} \equiv \frac{k_0 - k_3}{m}$. T^h is the amplitude for the hard pp elastic scatterings, T^s is the amplitude for soft pn rescatterings and $\psi(\alpha, p_t)$ is the deuteron light cone wave function. Spin effects are not included. The labels "b", "c" and "d" correspond to the diagrams in Fig.4. It is well known that the sum of these diagrams leads to lowest order formulae of the eikonal approximation where the intermediate particles are on the mass shell. We calculate only the diagram "b" since the calculation for the other two rescattering diagrams is practically identical. In terms of light cone variables k (k_+, k_-, k_t) the invariant phase volume is $d^4 k \rightarrow \frac{1}{2} dk_+ dk_- dk_t$ and the denominator of integrand "b" is given by:

$$\begin{aligned}
& ((p_s - k)^2 - m^2 + i\varepsilon)((p_1 - k)^2 - m^2 + i\varepsilon) = \\
& (p_1 - k)_+ \left[p_{1-} - k_- - \frac{m^2 + (p_1 - k)_t^2}{p_{1+} - k_+} + i \frac{\varepsilon}{p_{1+} - k_+} \right] \cdot \\
& (p_s - k)_- \left[p_{s+} - k_+ - \frac{m^2 + (p_1 - k)_t^2}{p_{s-} - k_-} + i \frac{\varepsilon}{p_{s-} - k_-} \right]
\end{aligned} \tag{11}$$

To evaluate the integral we take residues over dk_+ and dk_- which correspond to on-shell intermediate nucleons (namely the incident proton and spectator neutron). Finally, for

diagram "b" we obtain:

$${}^{\text{b}} = \frac{i}{4} \int \frac{T^h(s, t') \cdot T^s(k)}{s_1} \cdot \psi(\alpha + \alpha_k, p_t + k_t) \cdot \frac{d^2 k_t}{(2\pi)^2} \Big|_{k_- = p_{1-} - \frac{m^2 + (p_s - k)^2}{p_{1+} - k_+}} \quad (12)$$

where $s_1 = (p_1 - k)_+(p_s - k)_- \approx p_{1+}p_{s-}$ is the center of mass energy for the incident proton and the spectator neutron rescattering. As follows from eq. (12) at sufficiently high energies and soft rescatterings $k_- \approx 0$ and $\alpha' \approx \alpha$ and therefore the longitudinal (α) component of wave function is not changed by the soft rescattering.

Similarly, for the diagrams "d" and "c" one gets the following expressions:

$$\begin{aligned} {}^{\text{c}} &= \frac{i}{4} \int \frac{T^h(s', t') \cdot T^s(k)}{s_3} \cdot \psi(\alpha + \alpha_k, p_t + k_t) \cdot \frac{d^2 k_t}{(2\pi)^2} \\ {}^{\text{d}} &= \frac{i}{4} \int \frac{T^h(s', t) \cdot T^s(k)}{s_4} \cdot \psi(\alpha + \alpha_k, p_t + k_t) \cdot \frac{d^2 k_t}{(2\pi)^2} \end{aligned} \quad (13)$$

where the $s_3 \approx p_{3+}p_{s-}$ and $s_4 \approx p_{4+}p_{s-}$ are the invariant energies corresponding to rescattering of the scattered and produced protons with the spectator neutron.

For soft rescattering $T^s(k)/s$ is practically independent to s . Since the dependence on t of the hard scattering is slower than the exponential dependence of soft rescattering, one can neglect the difference between t and t' in the hard scattering amplitude. As a result we find that the diagrams of "b", "c" and "d" contribute equally. Therefore, the scattering amplitude can be expressed by the sum of the Born diagram plus three times the contribution of any one of the diagrams "b", "c", "d". Factorizing the hard scattering amplitude from this sum, including the spin dependence of the deuteron wave function and taking the square of the amplitude we obtain the final expression for the effect of initial and final state interaction which is presented in eq. (6). For simplicity we neglect the effects of spin rotation in the light cone spin density function of the deuteron (see [19]) which is a small effect (1%) in our case.

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Figure Captions

- Fig. 1. $F(s, \Theta_{cm})$ is the function used to best fit the world data for pp elastic scattering to the phenomenological motivated parametrization of [16] and [17]. The parametrization is ideal for large ($\geq 10 \text{ GeV}^2$) s and $\Theta_{cm} \rightarrow 90^\circ$ and under this condition $F(s, \Theta_{cm}) \rightarrow 1$.
- Fig. 2. The LC PWIA cross sections for hard quasielastic proton scattering of the deuteron as a function of the momentum (p_s) and polar angle (θ_s) of the spectator neutron. (a) - $p_1 = 6 \text{ GeV}/c$, (b) - $p_1 = 12 \text{ GeV}/c$.
- Fig. 3. The ratio of LC PWIA cross sections. In the nominator the cross section for pp hard scattering was calculated with a final state invariant energy s and the denominator cross section was calculated for the invariant energy of the intermediate state. The ratio is presented as a function of the spectator momenta ($\theta_s = 180^\circ$). The dashed line is for $p_1 = 6 \text{ GeV}/c$ and the solid line is for $p_1 = 12 \text{ GeV}/c$.
- Fig. 4. The diagrams show the PWIA and the lowest order soft pn rescattering processes. The broken line represents the soft interaction. The empty circles represent the hard pp scattering vertices.
- Fig. 5. The factor κ_p represents the effect of ISI and FSI as calculated in eikonal approximation according to the diagrams of Fig.4. The projectile momentum is $p_1 = 12 \text{ GeV}/c$. The different lines (from top to bottom) correspond to spectator transverse momenta of 0, 40, 80, 120, 160 MeV/c .
- Fig. 6. Time-ordered diagrams representing the impulse approximation contribution (A) and the relativistic (vacuum) contribution (B).
- Fig. 7. The ratio of the cross sections as a function of p_s calculated in LC over the cross section obtained in the VN approximation for $p_1 = 12 \text{ GeV}/c$. (a) parallel and antiparallel geometries, (b) perpendicular geometries (see definitions in Section 2).

The solid line is for the PWIA calculation with the "Paris" deuteron wave function. The dashed line is for the PWIA calculation with the "Bonn" wave function. The curves with " \diamond " correspond to the calculation with ISI and FSI.

Fig. 8. The $\delta(p_s)$ dependence of the asymmetry A defined in eq.(8) and calculated in the VN approximation. $p_1 = 12 \text{ GeV}/c$. The lines and symbols are defined in the previous figure. Note that $A = 0$ in LC. The bottom scale represents the corresponding values of longitudinal component of the spectator momenta p_{sz} calculated for $\alpha = 1 - \delta$ (negative p_{sz}) and $\alpha = 1 + \delta$ (positive p_{sz}) at $\delta = 0.1, 0.2$ and 0.3 .

Fig. 9. The ratio of cross sections calculated in the LC approximation with and without taking into account the PLC suppression. The ratio is shown as a function of p_s for parallel (solid), antiparallel (dashed) and perpendicular (dot-dashed) geometries. The calculations are presented for $p_1 = 12 \text{ GeV}/c$ with the "Paris" wave function for the deuteron.

Fig. 10. The cross section for $p_1 = 12 \text{ GeV}/c$ of hard quasielastic pd scatterings as a function of spectator momentum at (anti)parallel geometries. Dotted line - VN PWIA, dash-dotted - LC PWIA, dashed - LC with the effect of PLC suppression and solid line - LC with PLC suppression and with ISI, FSI. The "Paris" wave function for the deuteron was used.

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